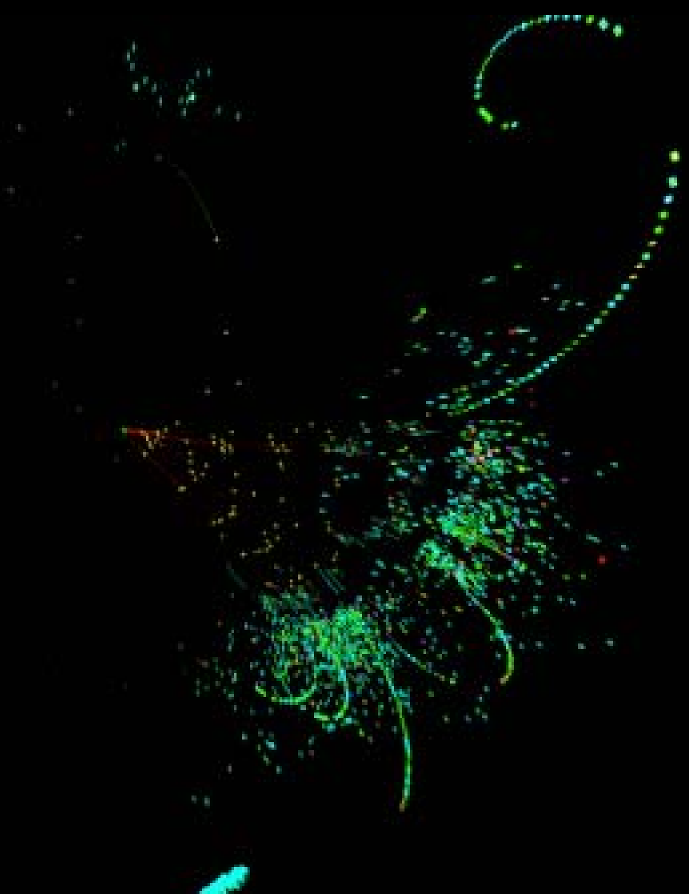
Matter, Energy, Space and Time:

Particle Physics in the 21st Century



Jonathan Bagger

May 8, 2003

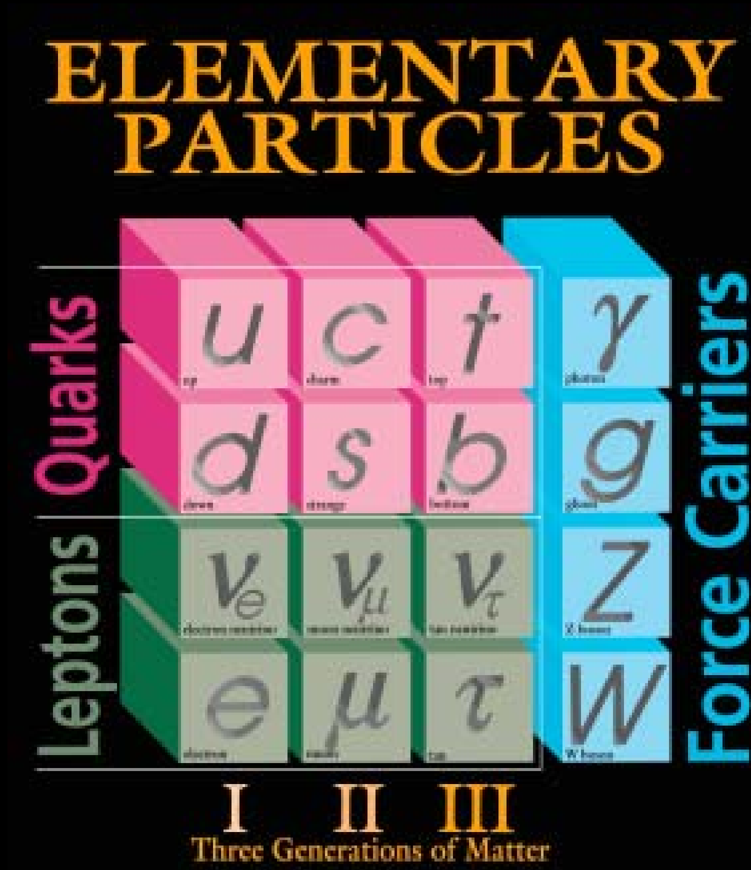
A Century of Physics

- The 20th century witnessed the triumph physics
  - From the discovery of the electron and the nucleus
  - To the development of relativity and quantum mechanics
- We now have an understanding of the basic physical processes that underlie our everyday world
  - With applications that have transformed our way of life
- At the dawn of the 21st century, we are poised to answer new questions
  - At the frontiers of the very complex, the very large, and the very small

Particle Physics

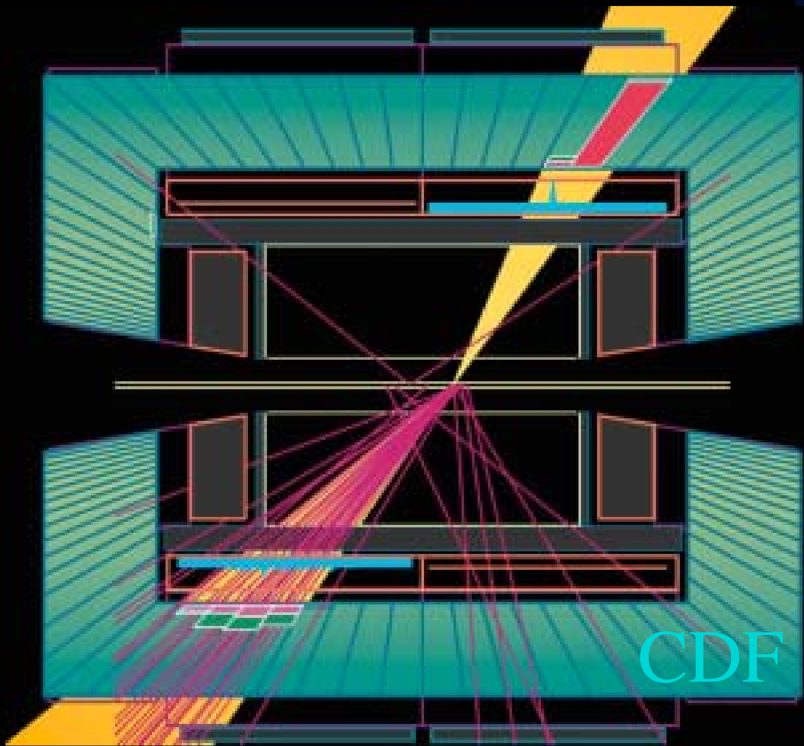
- Particle physics has been at the center of this revolution

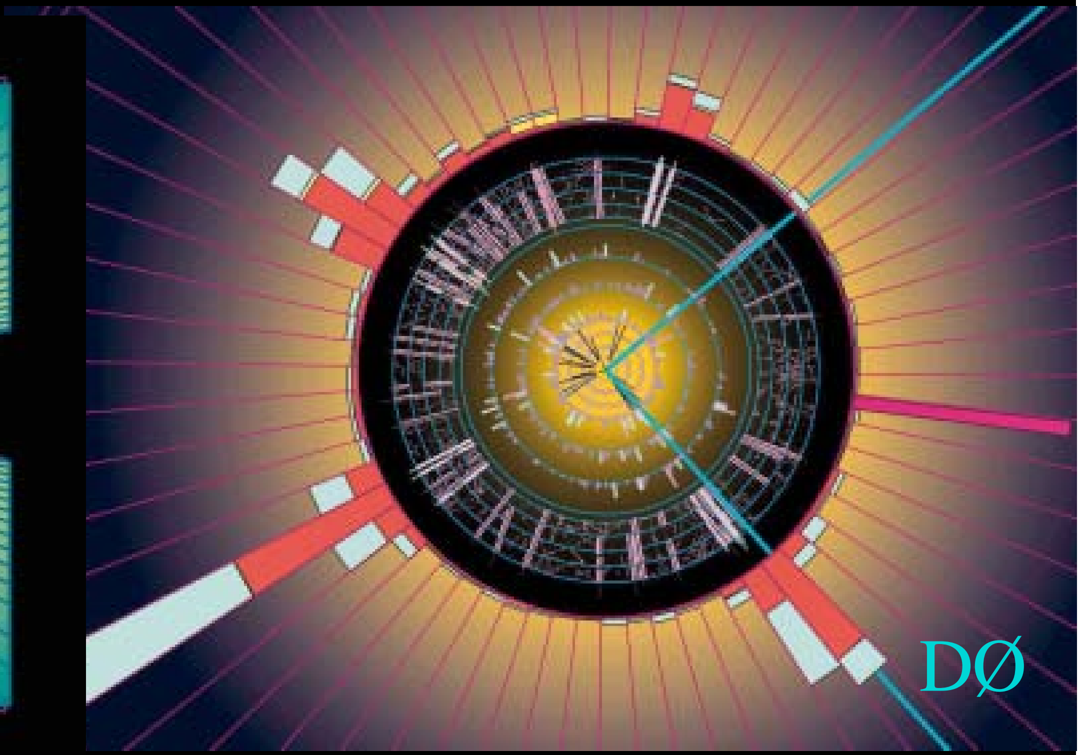
- After 50 years of intense effort, we now know that the physical world is
  - Composed of quarks and leptons
  - Interacting via force carriers called gauge bosons



Standard Model

- The final pieces fell into place only recently
  - 1995: Discovery of the top quark at Fermilab





Standard Model

- 1990–2000: Precision measurements from many sources, especially CERN

We now have a precise and quantitative description of subatomic physics, valid to the 0.1% level

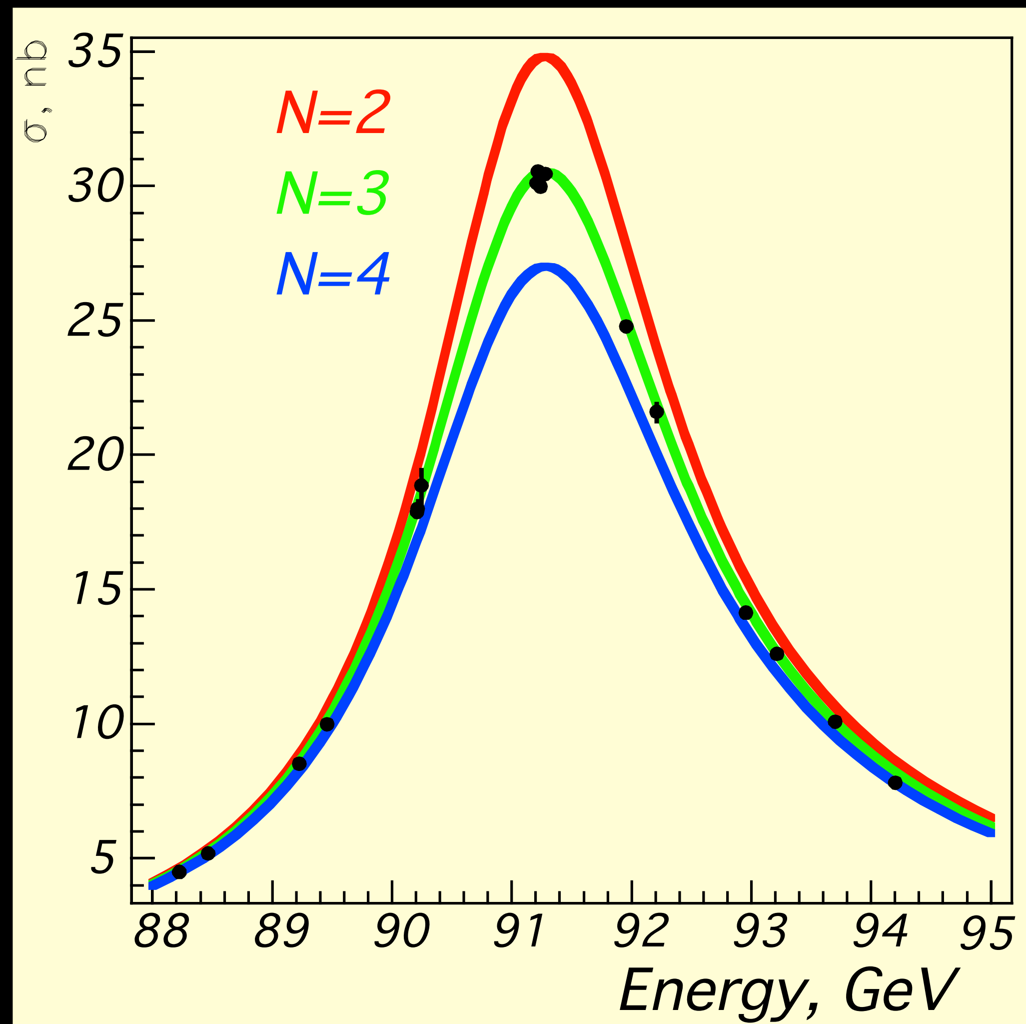
LEP EWWG

Standard Model

– And that's it!

$N_\nu = 2.994 \pm 0.012$

DELPHI



Present Status

- So, the evidence suggests, particle physics is finished …

… or is it?

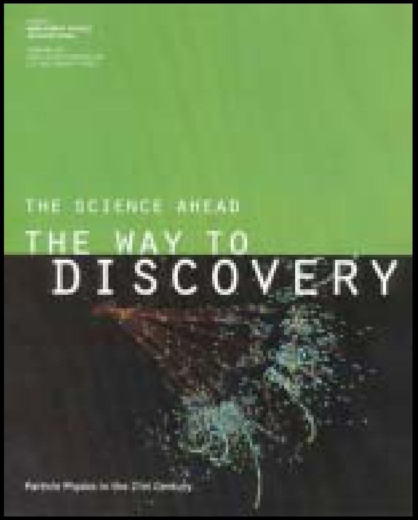
- In fact, we shall see that a variety of clues pose new puzzles – that will be at the heart of particle physics in the 21st century

HEPAP Subpanel

- The recent HEPAP subpanel looked closely at these issues, and developed a strategic plan for the next twenty years
- It concluded that particle physics is about to enter a new era …
  - Exploring physics beyond the Standard Model
  - Addressing deep new questions about the nature of matter and energy, space and time

HEPAP Report

- The panel's report lays out a path to answer the questions
- It shows that particle physics has a bright future. The field is poised to enter a new era of discovery, one every bit as exciting as what we have seen before …



Scientific Themes

- The report expressed the field's scientific goals in terms of three grand themes
  - Ultimate Unification
  - Hidden Dimensions
  - Cosmic Connections

Ultimate Unification

What are the ultimate laws of nature?

- Are there new forces, beyond what we see today?
- Do the forces unify? At what scale?
- What lies beyond the quarks and the leptons?
- What completes the Standard Model?
- How do neutrinos fit in the picture?
- Why is gravity so different from the other forces?

The search for the DNA of matter

Hidden Dimensions

What is the structure of space and time?

- Why are there four spacetime dimensions?
- Are there more? What are their shapes and sizes?
- Are they classical or quantum?
- What is the state of the vacuum?
- What is the origin of mass?
- What is the quantum theory of gravity?

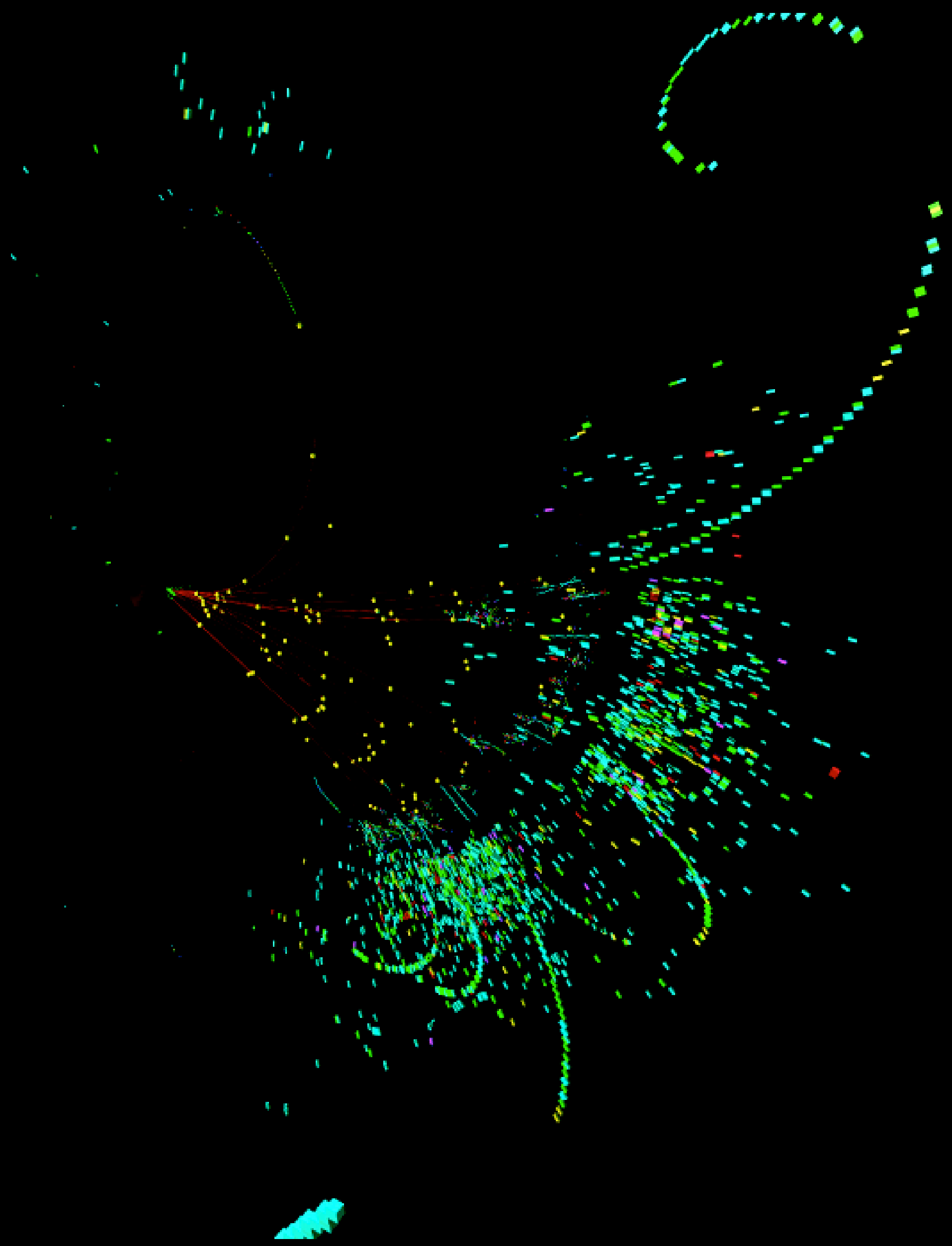
From science fiction to science fact

Cosmic Connections

How did the Universe come to be?

– What is the dark matter and dark energy?
– What happened to antimatter?
– Do the constants of nature change with time?
– What powered the Big Bang?
– What is the fate of the Universe?

The inner-space outer-space connection



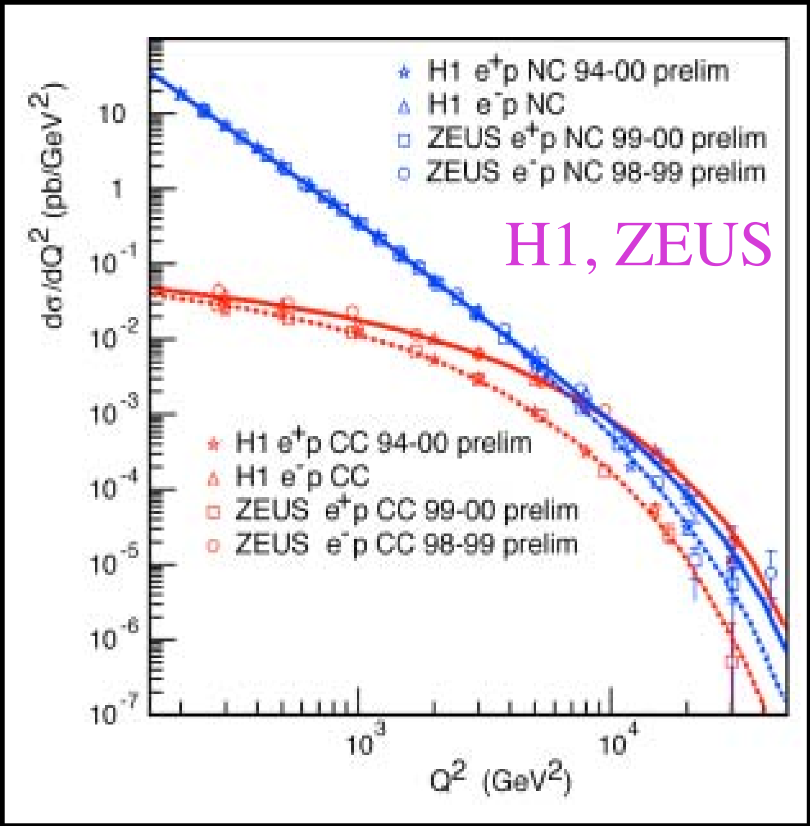
Ultimate Unification

Ultimate Unification

- Unification has a long and distinguished history in physics
  - Newton: Apples and planets
  - Maxwell: Electricity and magnetism
  - Einstein: Space and time
  - Dirac: Relativity and quantum mechanics
  - Glashow, Salam, Weinberg: Weak and electromagnetic interactions

Electroweak Unification

- We are on the verge of experimentally testing electroweak unification
- But unification requires new ingredients …



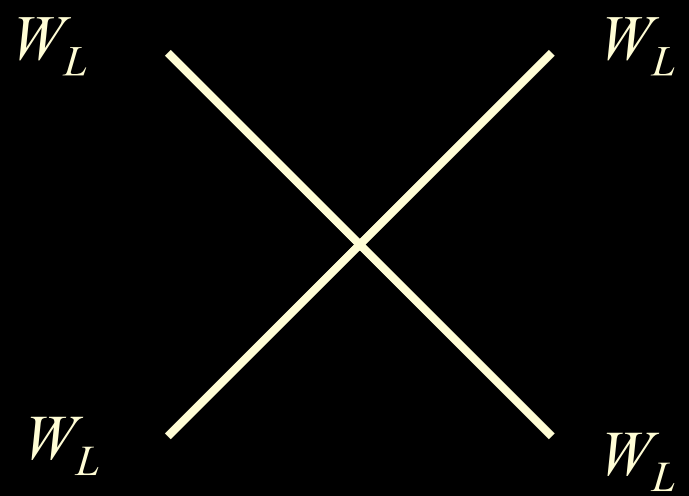
HERA *ep* collider

Higgs Boson

- Thought experiment:

  $W_L W_L$ scattering

- The Standard Model is mathematically inconsistent unless there is new physics below about 1 TeV

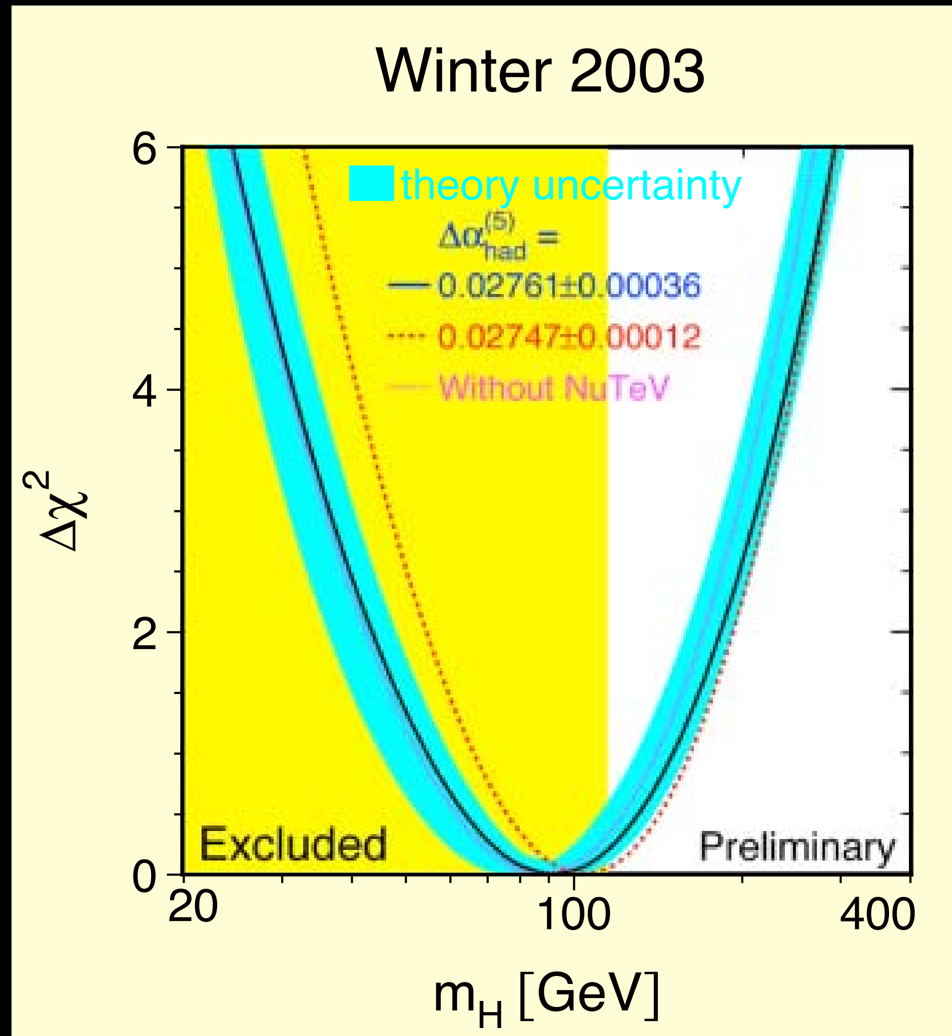


Probability ~ $(E/1\ \text{TeV})^2$

Higgs Boson

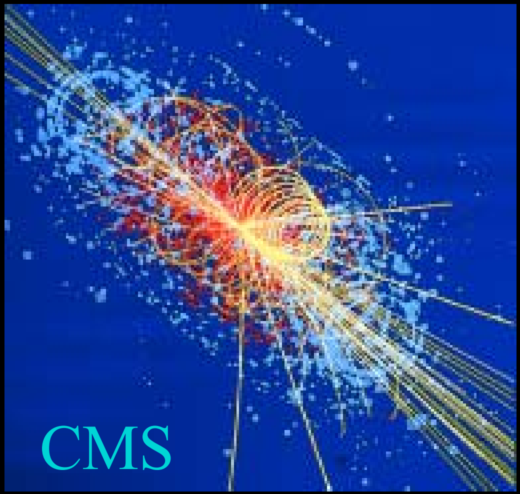
- The simplest possibility is a Higgs boson
- Precision data suggest the Higgs is close at hand…

LEP EWWG



Higgs Discovery

- If there is a Higgs, it will soon be discovered
  - Perhaps at the Fermilab Tevatron
  - Certainly at the CERN LHC



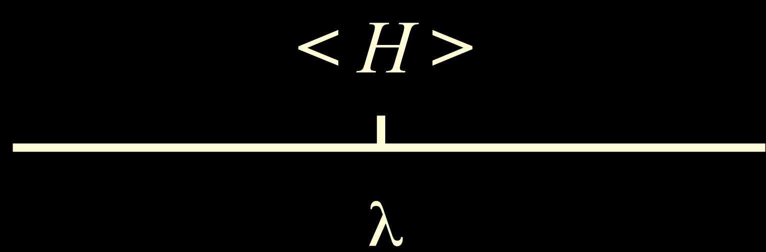
Higgs Revolution

- The discovery will revolutionize our field. The Higgs is new form of matter!
  - A fundamental spin-zero particle
  - A new force that couples to mass

The Higgs is radically different than anything we have seen before …

Higgs Revolution

- The Higgs permeates the vacuum and gives mass to the elementary particles



$$M \sim \lambda < H >$$

The Higgs fills the Universe with a Bose-Einstein condensate, responsible for the origin of mass

A New Set of Questions

- Of course, once we find a "Higgs," we must be sure it is *the* Higgs …
  - Does the particle have spin zero, as required?
  - Does it generate masses for the *W* and *Z*, and for the quarks and leptons?
  - Does the it generate its own mass?

We need precision experiments to know for sure

Linear Collider

- Such experiments will require a new tool – in addition to the LHC…

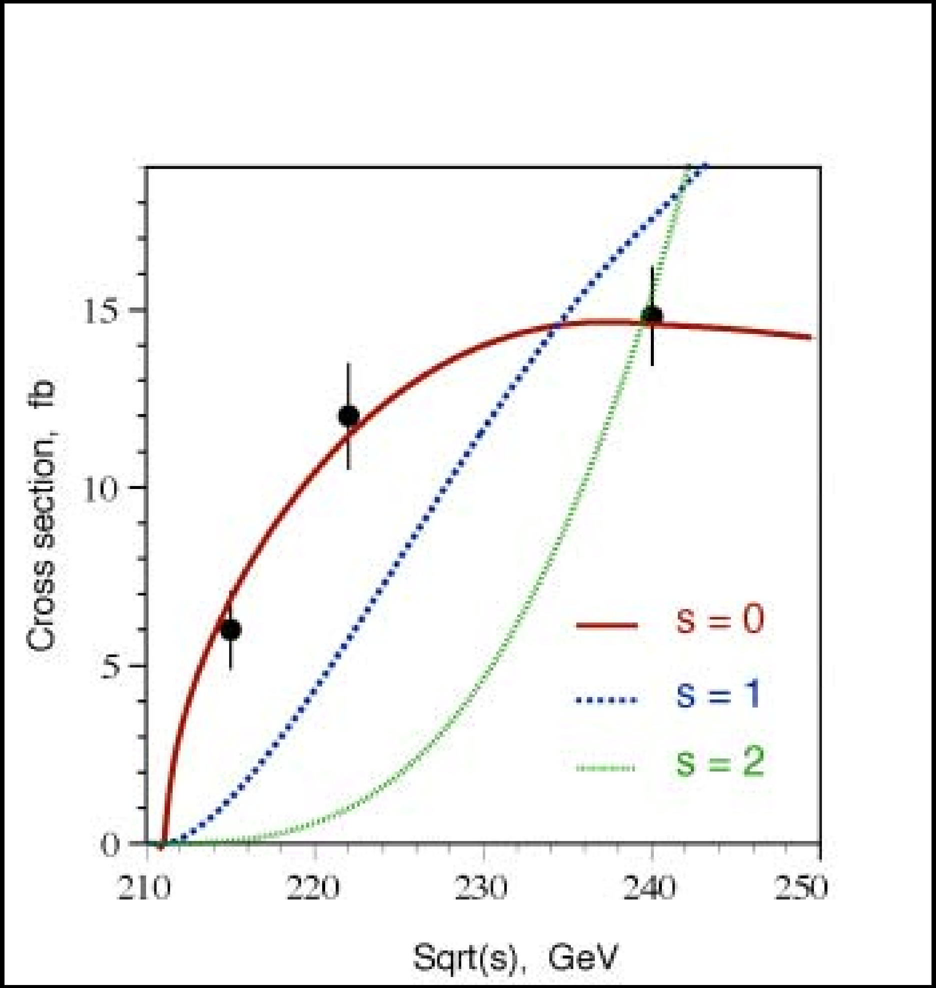
- An electron-positron linear collider, with detectors capable of precision measurements at the TeV scale …

Linear Collider

Linear Collider

- A linear collider will measure spin

The Higgs must have spin zero



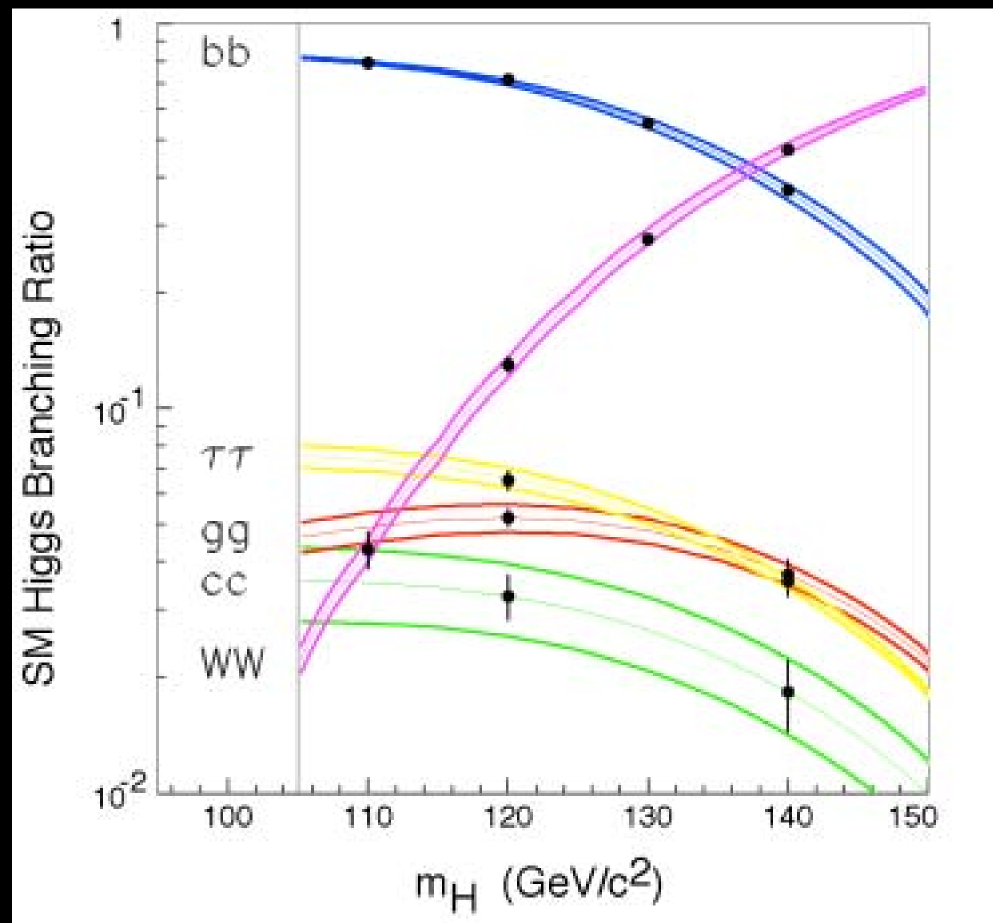
Dova, Garcia-Abia, Lohmann

Linear Collider

- It will also measure branching fractions

The Higgs must also have couplings proportional to the masses of the particles

Battaglia



Beyond the Higgs

- By the end of the decade, we will have our first glimpse of this new physics, whatever it well may be
- But the new physics will raise new questions
- As we will see, these questions point to even more discoveries at the TeV scale

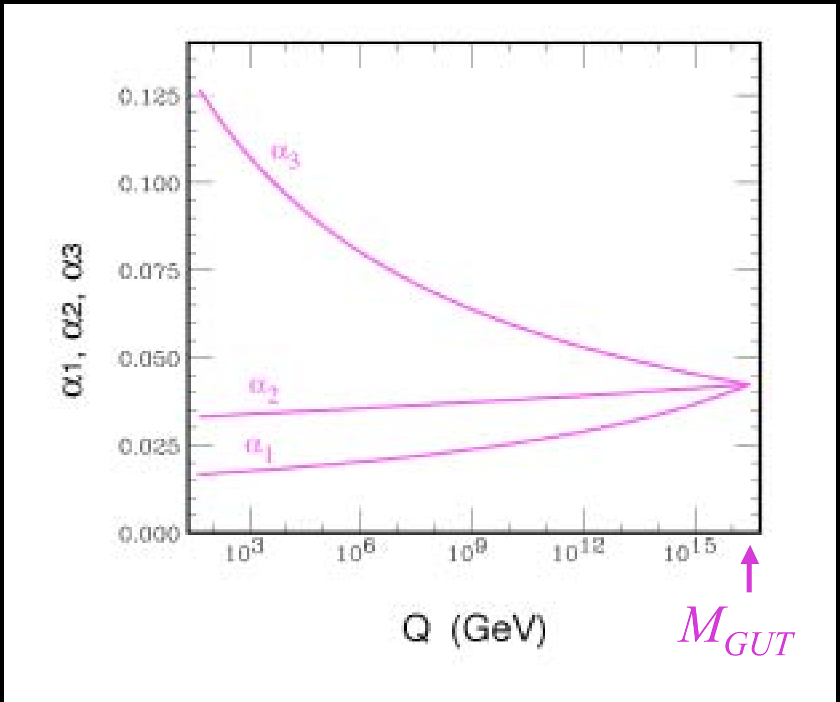
Electroweak unification opens the door to physics beyond the Standard Model

For Example …

- Why is M_W about 100 GeV, and not M_{Pl}?
  - Are there new particles?
    - Gauge bosons are light because of gauge symmetry. Is the Higgs light because of *supersymmetry?*
  - Are there new forces?
    - Are there new strong interactions, like *technicolor,* that operate at the TeV scale?
  - Does physics end at a TeV?
    - Does gravity become strong at the TeV scale? Are there new *hidden dimensions?*

Supersymmetry

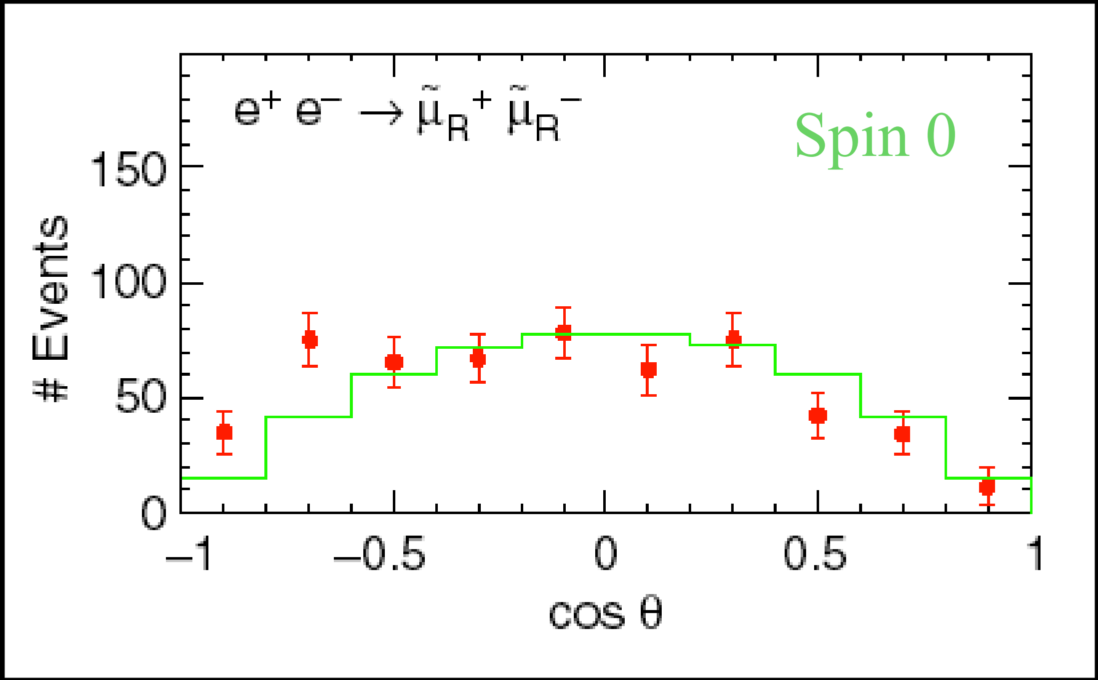
- Supersymmetry unifies matter with forces
  - Every known particle has a supersymmetric partner, of opposite statistics
- It might also unify the electroweak and strong interactions
  - Already, there are hints in the data …



Testing Supersymmetry

- If we find new "superparticles," we need to measure their spins and couplings
  - Do the spins differ by 1/2?
  - Are the couplings correct?

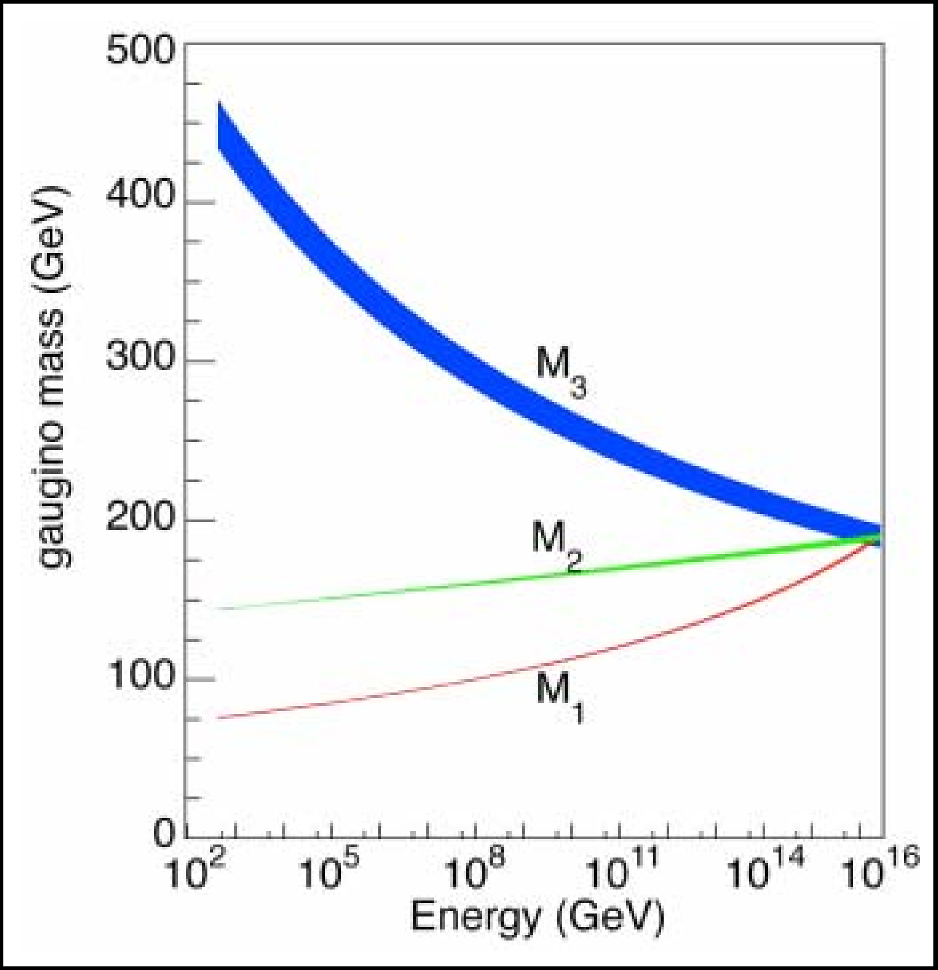
A linear collider is ideal for the job



Tsukamoto, Fujii, Murayama, Yamaguchi, Okada

Supersymmetric Unification

- The supersymmetric particles themselves might unify at high energies
- Such measurements require both the LHC and a linear collider

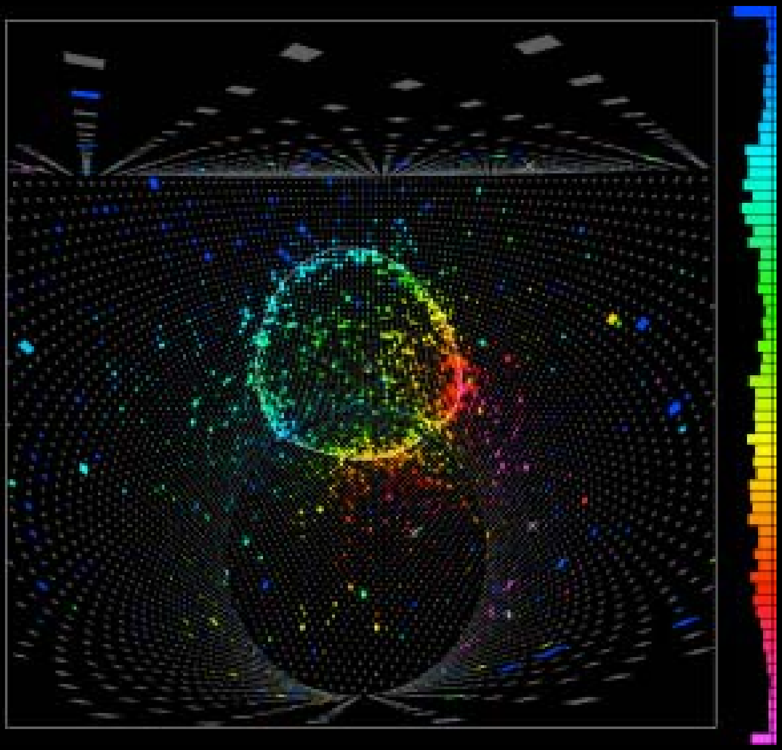


Blair, Porod, Zerwas

Supersymmetric Unification

- If the forces unify, the proton can be unstable, and eventually decay …

- The discovery of supersymmetry would give added impetus to these



Super-Kamiokande

Neutrinos

- The discovery that neutrinos have mass was one of the great events of the last few years
  - Neutrino masses are forbidden in the Standard Model, but necessary features of some unified theories
- We now know that as much of the mass of the Universe comes from neutrinos as from stars and galaxies

Neutrinos

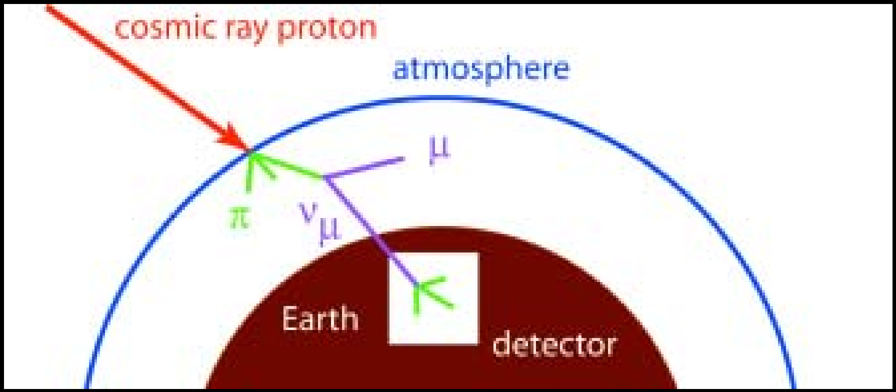
- Neutrinos penetrate anything, even popular culture

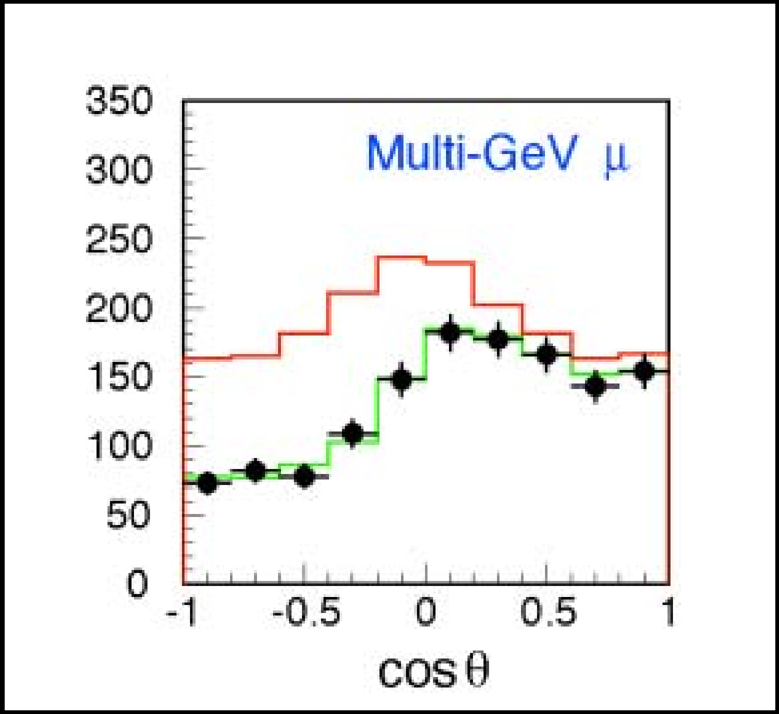
Neutrinos, by John Updike

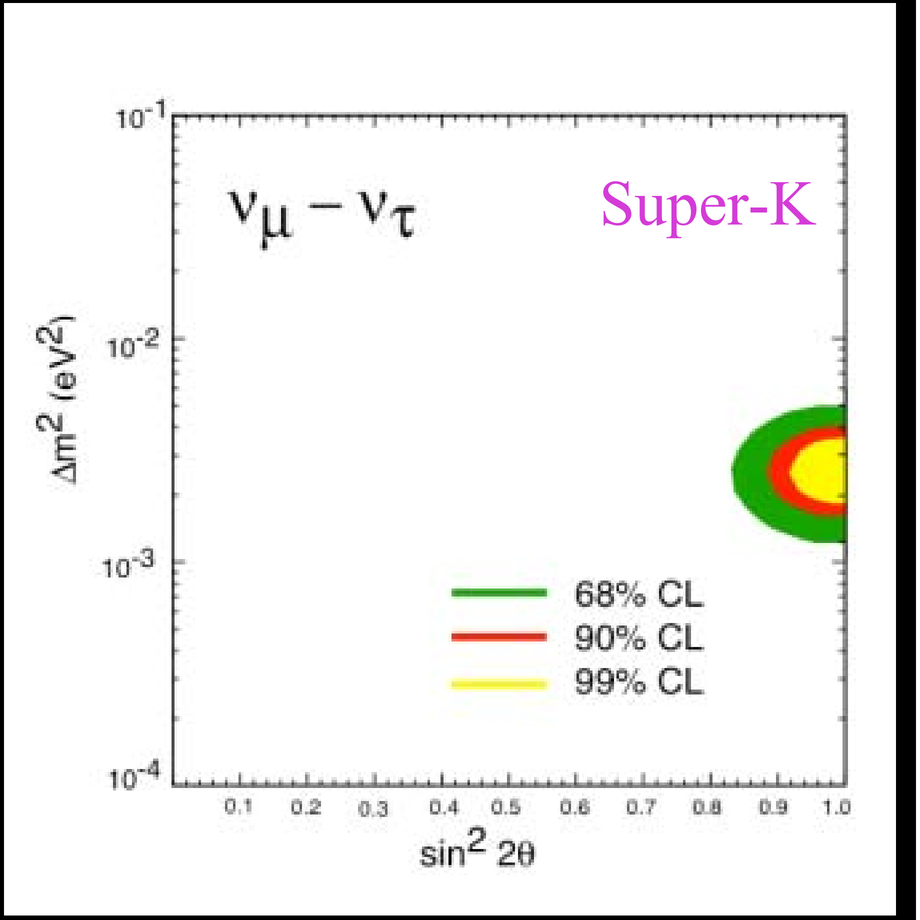
Neutrinos: they are very small
They have no charge; they have no mass;
They do not interact at all.
The Earth is just a silly ball
To them, through which they simply pass
Like dustmaids down a drafty hall
Or photons through a sheet of glass.
They snub the most exquisite gas,
Ignore the most substantial wall,
Cold shoulder steel and sounding brass,
Insult the stallion in his stall,
And, scorning barriers of class,
Infiltrate you and me. Like tall
And painless guillotines they fall
Down through our heads into the grass.
At night, they enter at Nepal
And pierce the lover and his lass
From underneath the bed. You call
It wonderful; I call it crass.

Atmospheric Neutrino Masses and Mixings

Super-Kamiokande: Half the atmospheric muon neutrinos are missing!







Solar Neutrino Masses and Mixings

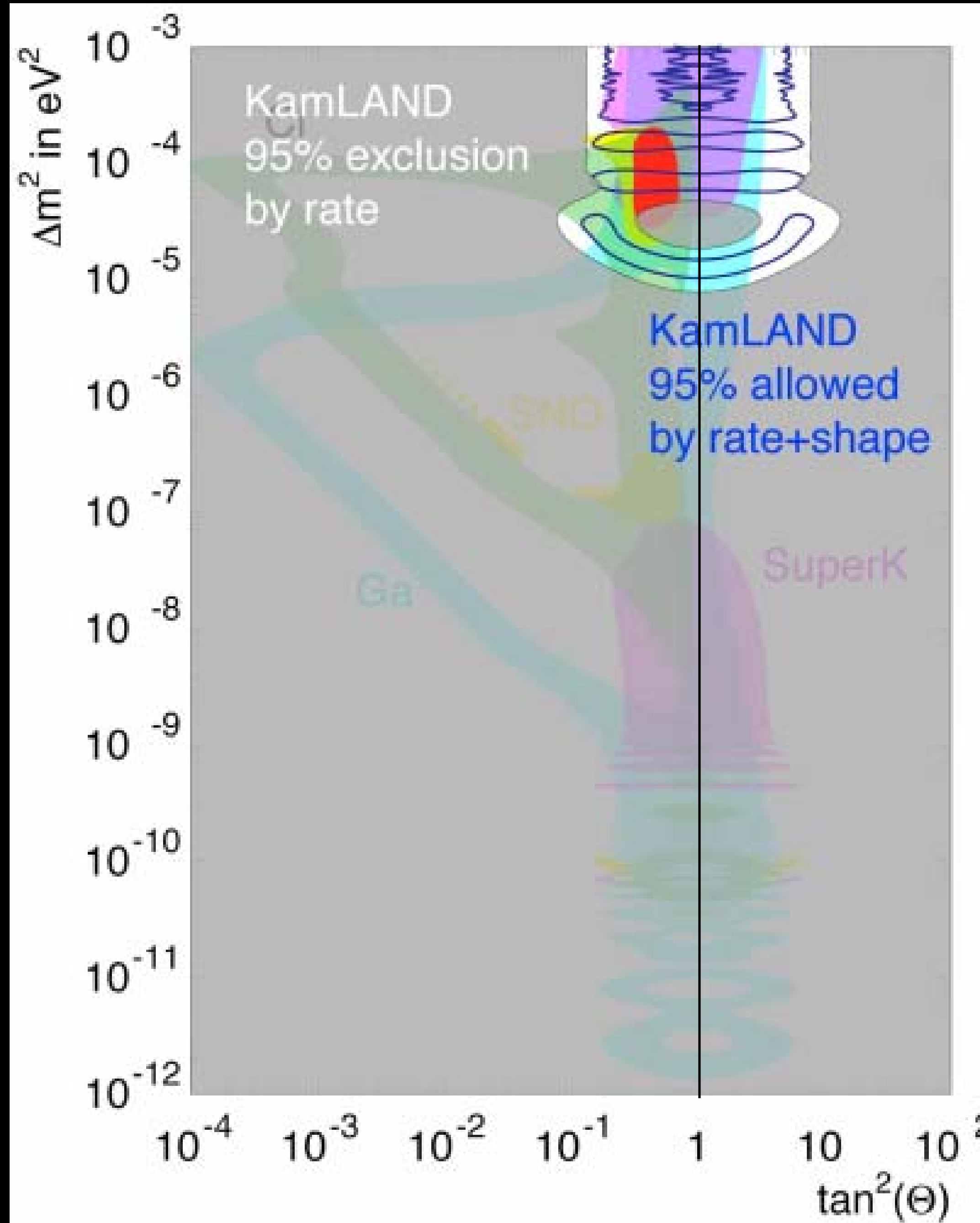
March 2002

April 2002 with SNO

Dec 2002 with KamLAND

The Sun

Murayama

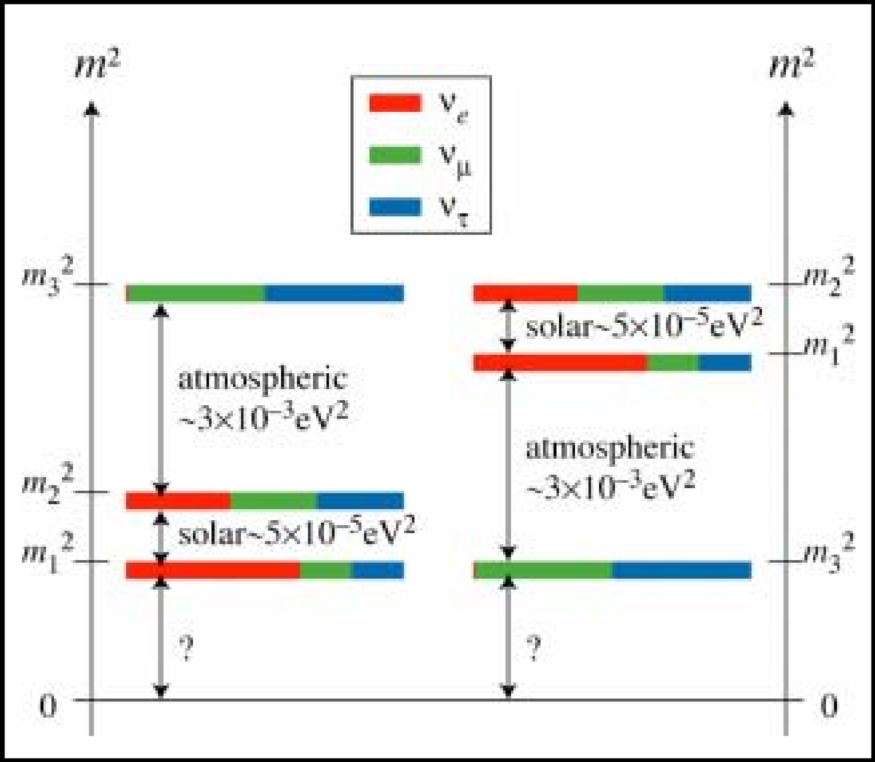


More Questions than Answers

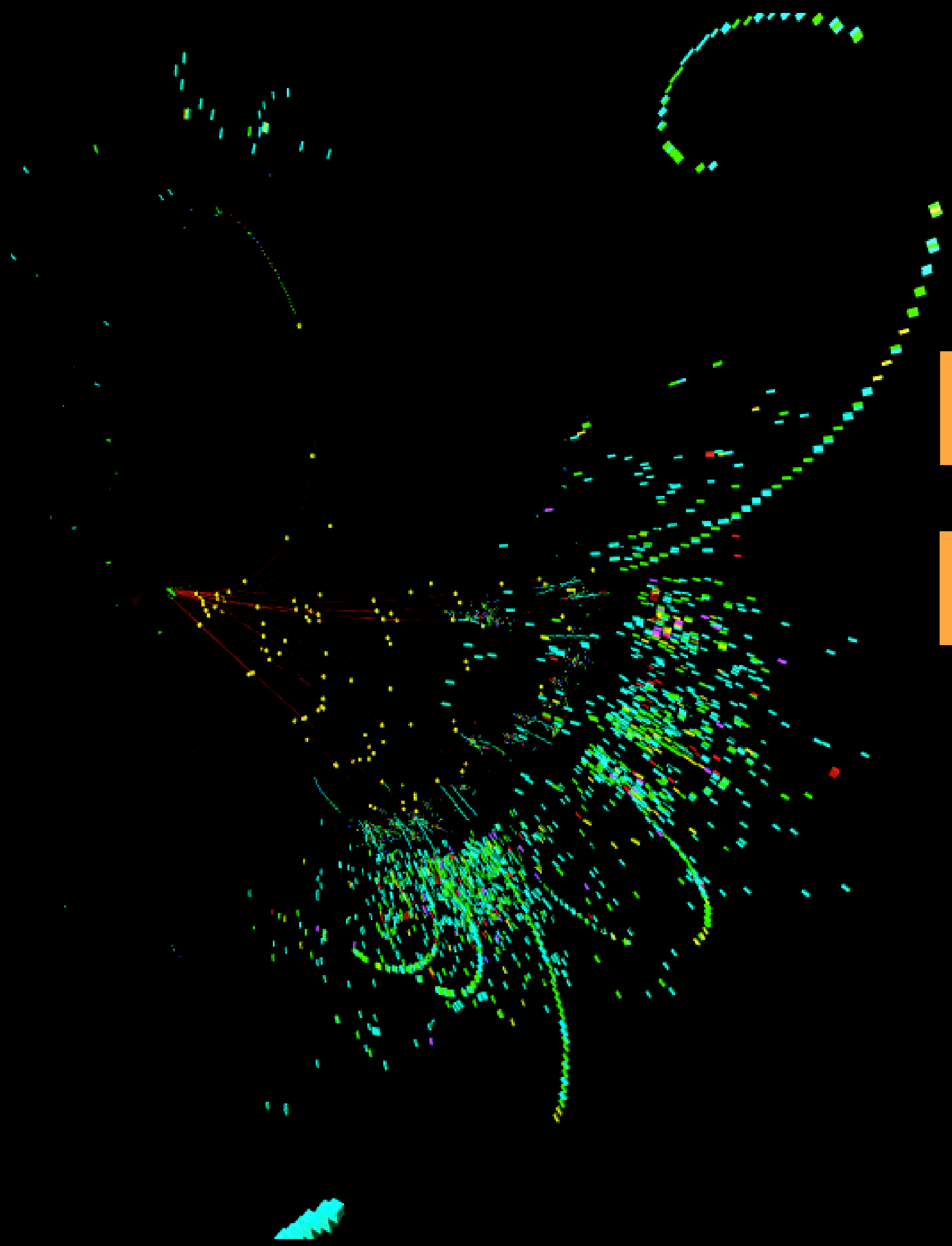
- Why do neutrinos have mass at all?
- Why are the masses so small?

$$m_\nu \sim (M_W)^2/M_{GUT}$$

- We know mass *differences*. What are the masses?
- Are there sterile neutrinos?
- Are neutrinos and anti-neutrinos the same?



Murayama



Hidden Dimensions

Hidden Dimensions

- The notion of extra dimensions is almost as old as relativity itself
  - From Kaluza and Klein
  - To Calabi and Yau

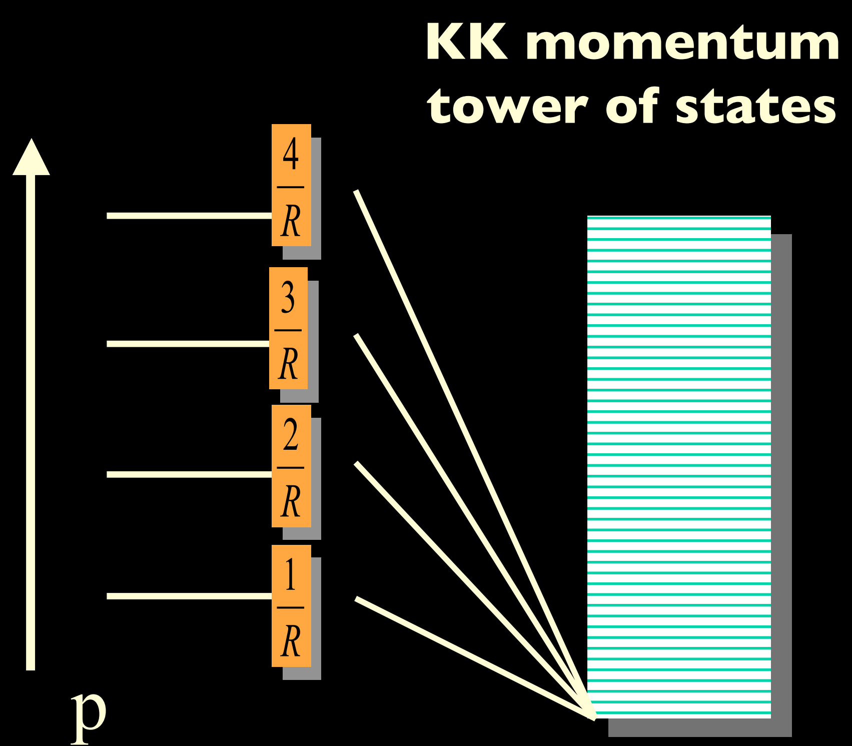
- Today, the idea receives additional support from string theory, which predicts new spacetime dimensions

Hidden Dimensions

- String theory also motivates brane models, in which our everyday world is confined to a membrane embedded in a higher-dimensional space
- Extra dimensions provide an explanation for the hierarchy $M_W << M_{Pl}$

Kaluza-Klein Particles

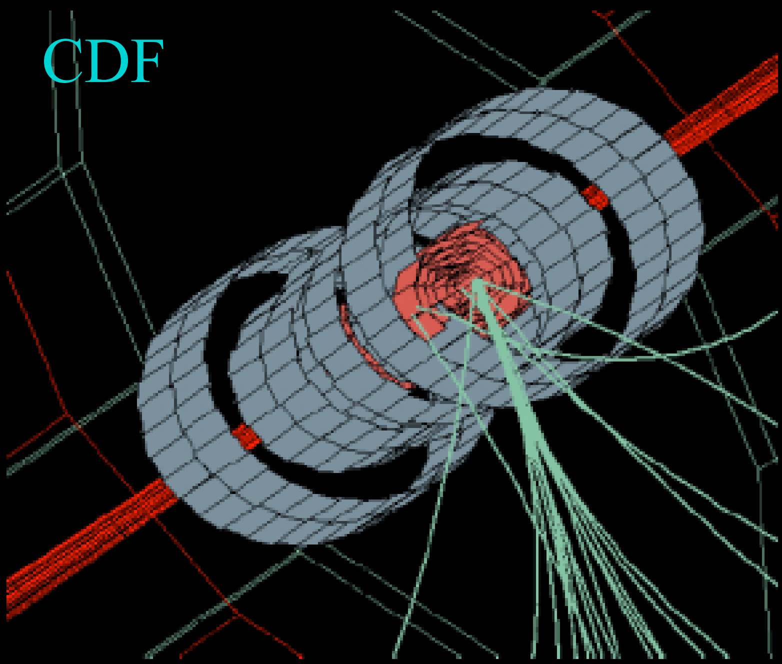
- Extra dimensions give rise to a tower of new Kaluza-Klein particles, with plenty to see at the TeV scale
  - New particles
  - Events with missing energy and momentum
  - SUSY?



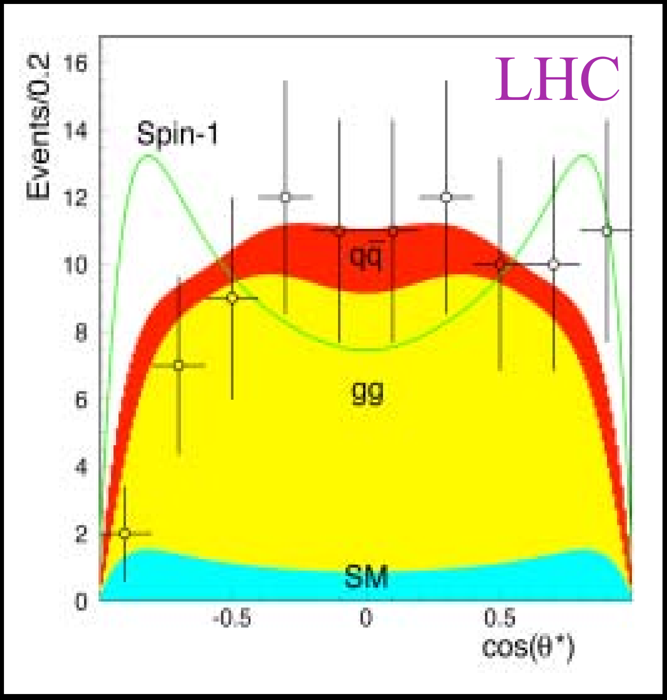
Lykken

Kaluza-Klein Particles

- We need to detect the Kaluza-Klein particles and measure their properties



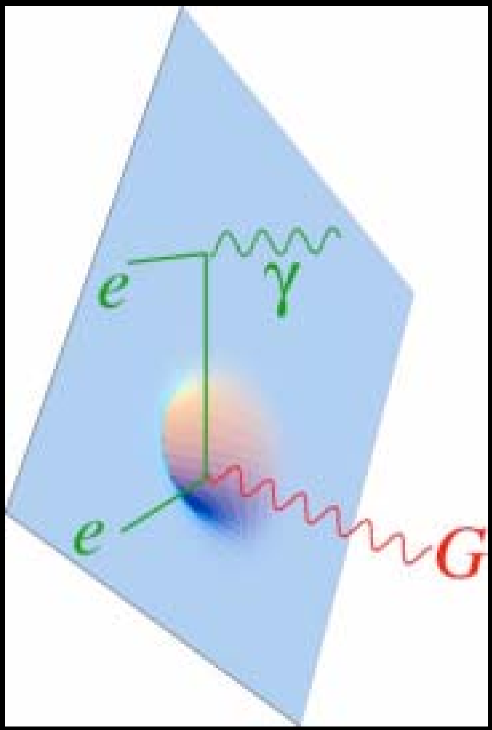
Spiropulu

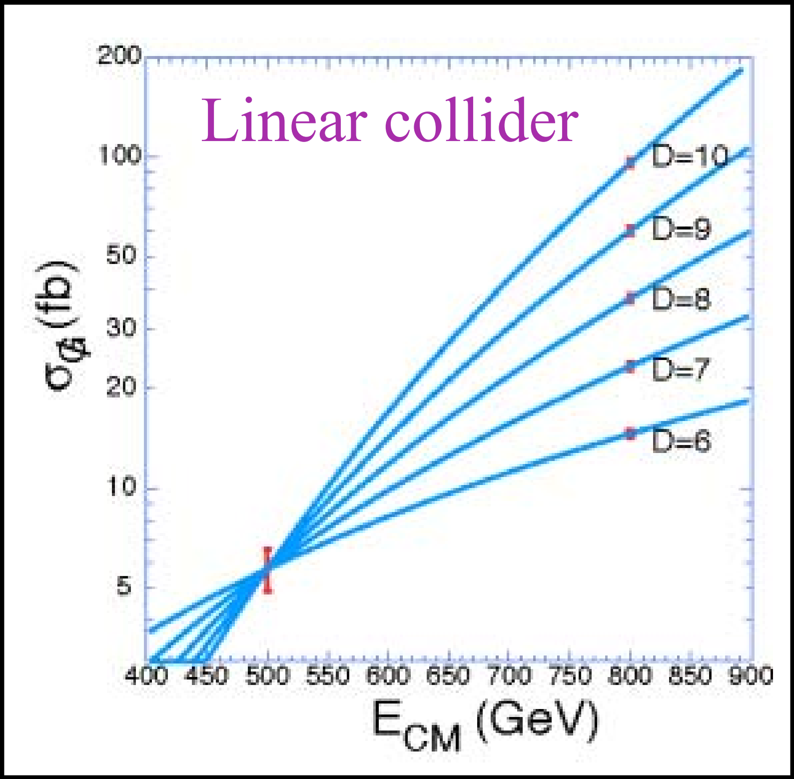


Allanach, Odagiri, Parker, Webber

How Many?

- Graviton emission can measure the number of hidden dimensions





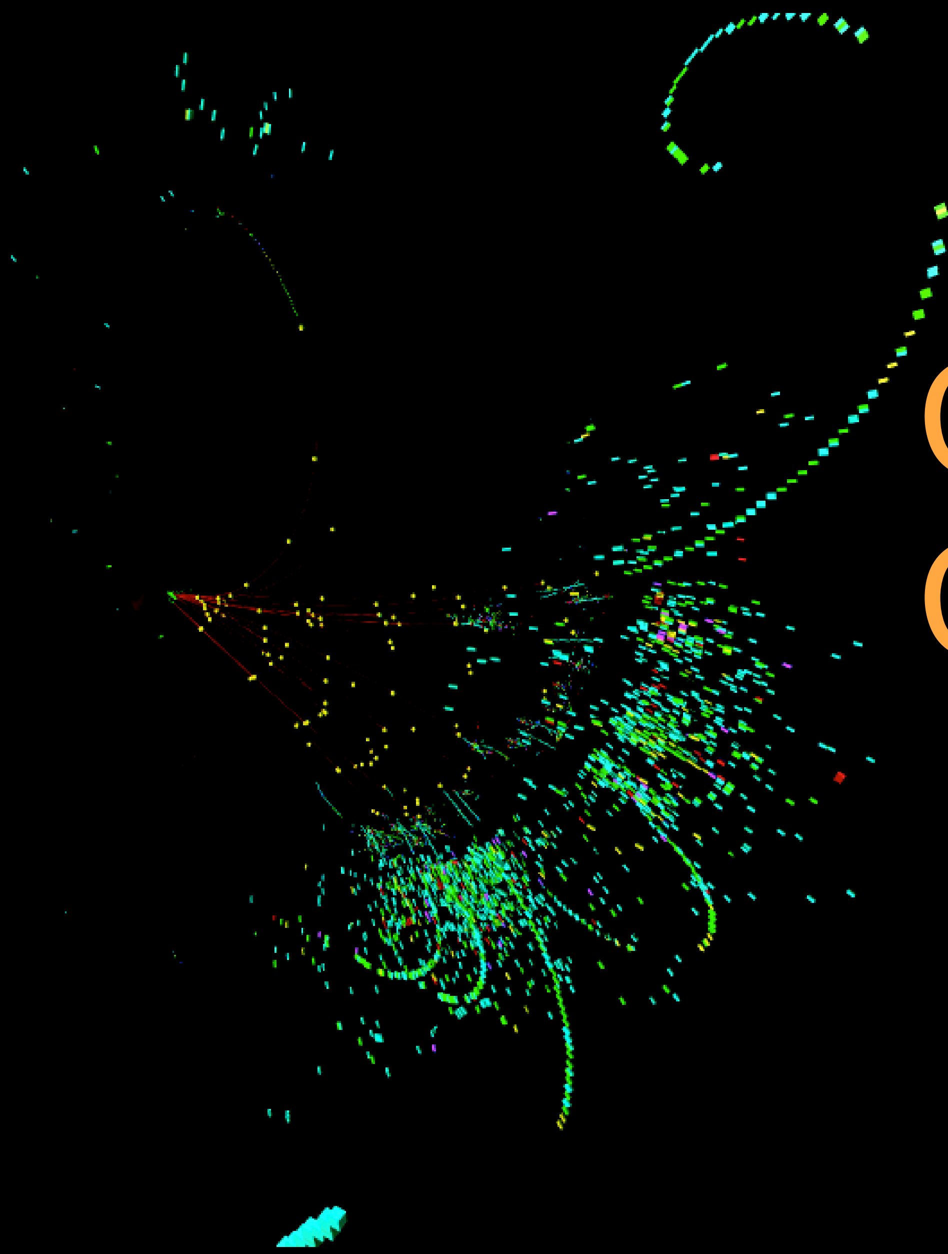
Wilson

Fermionic Dimensions

- Supersymmetry is also a consequence of a hidden spacetime dimension
  - A fermionic *quantum* dimension
- Quantum superfields contain bosons *and* fermions

$$\Phi(x,\theta) = \phi(x) + \theta\,\psi(x)$$

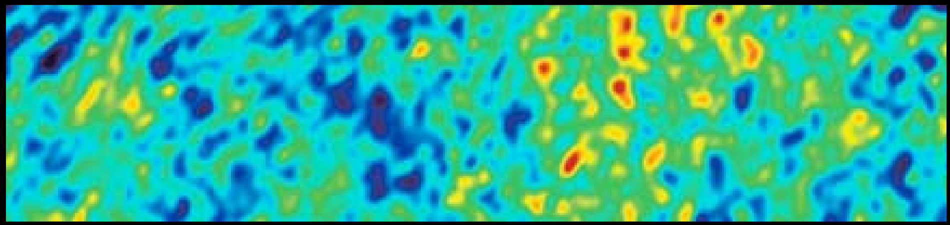
New dimensions show up as new particles



Cosmic Connections

Cosmic Connections

- With the results of WMAP – and other recent observations – cosmology has become a precision science, just like particle physics
  - The Universe is 13.7 ± 0.2 billion years old
  - The Universe is geometrically flat, $\Omega = 1.02 \pm 0.02$
- It points to new particle physics, beyond the Standard Model

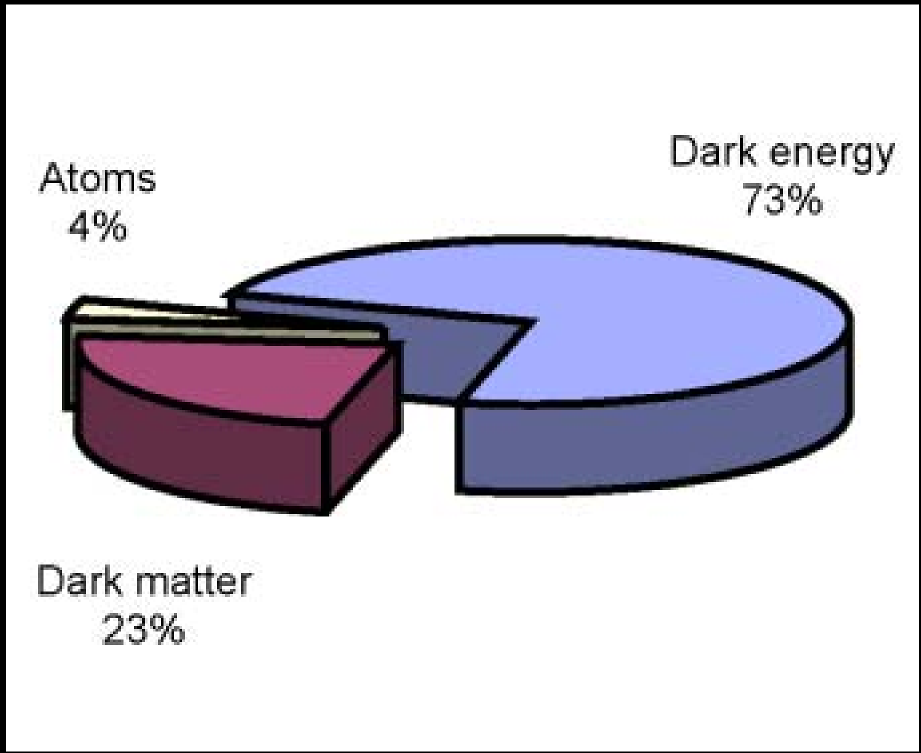


WMAP

Cosmic Connections

- Energy budget of Universe
  - Antimatter, 0%
  - Neutrinos, ~ 0%
  - Atoms, 4.4 ± 0.4%
  - Dark matter, 23 ± 4%
  - Dark energy, 73 ± 4%

96% is a mystery!




We understand the things we see
We don’t understand what we can’t
The Hubble Deep Field North
HUBBLESITE.org

Antimatter

10,000,000,001

q

10,000,000,000

$\bar{q}$

Early Universe

Antimatter

1 0

Cosmic Annihilation!

q $\bar{q}$

Today's Universe

Murayama

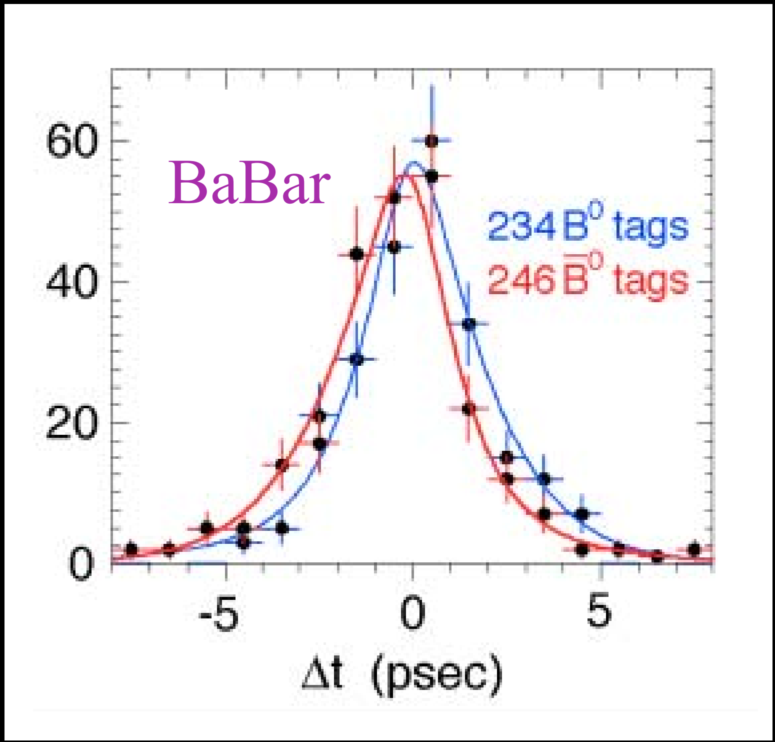
Matter over Antimatter

- What created this tiny excess of matter?
- Baryogenesis? Leptogenesis?

  Necessary conditions include
  - Baryon or lepton number non-conservation
  - CP violation (matter-antimatter asymmetry)
- Possible consequences in
  - Proton decay
  - Quark and lepton flavor physics

CP Violation

- Is anti-matter the exact mirror of matter?
- Recent progress
  - Precision measurement of CP violation in *B*-meson system
  - Agrees perfectly with the CKM picture of CP violation ….



SLAC and KEK B Factories

CP Violation

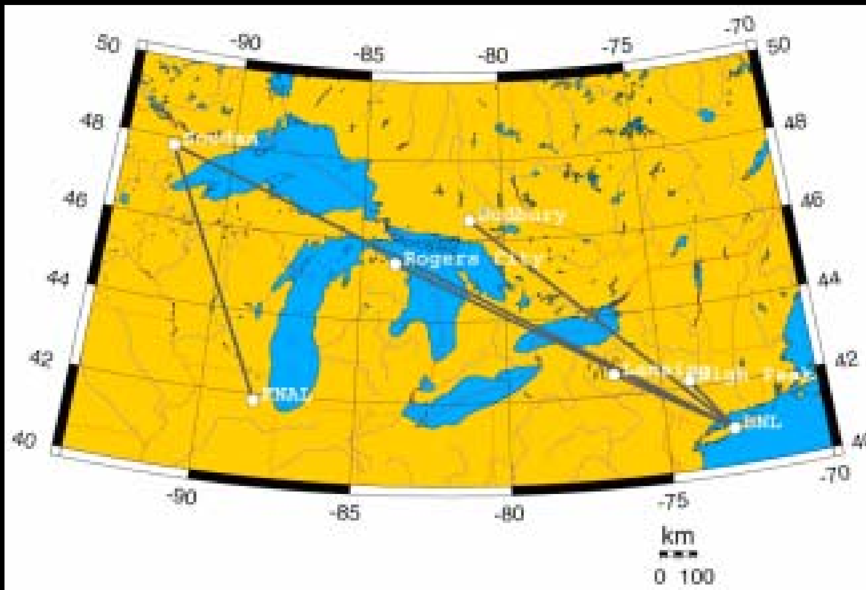
- There is not enough CP violation in the Standard Model for baryogenesis
- But there are new sources of CP violation in theories beyond the Standard Model …
  - Supersymmetric particles?
  - Neutrinos?

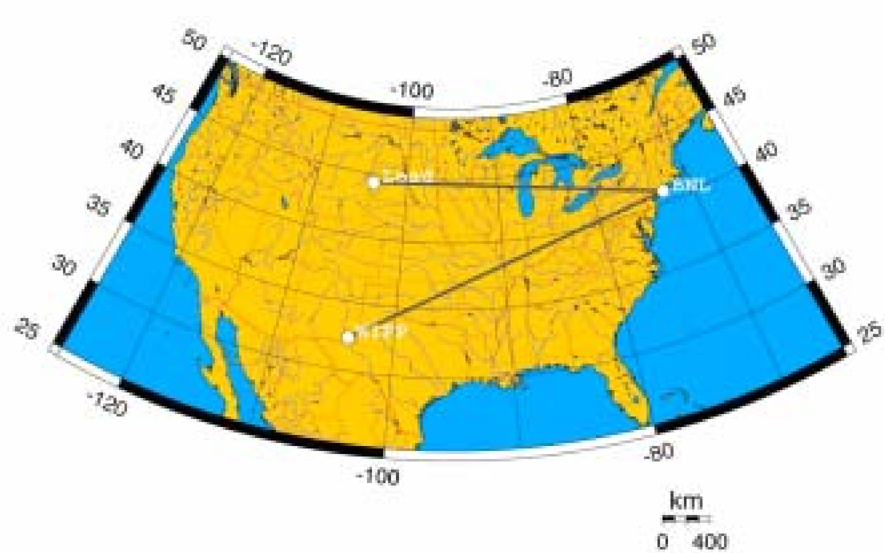
θ_{13}

$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23}$$
$$\sin\delta \sin\left(\frac{\Delta m_{12}^2}{4E} L\right) \sin\left(\frac{\Delta m_{13}^2}{4E} L\right) \sin\left(\frac{\Delta m_{23}^2}{4E} L\right)$$

$\not{CP}$

Long Baseline Experiments



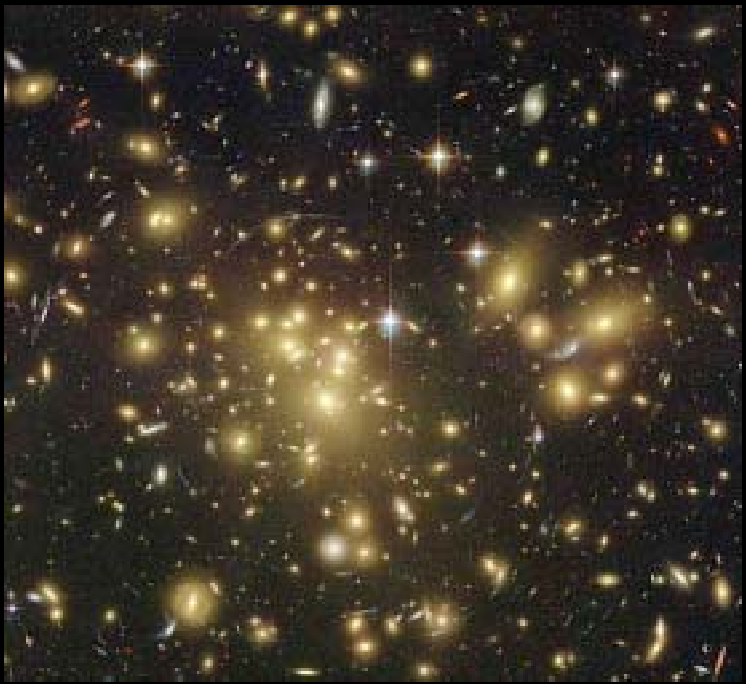


CP violation in the neutrino sector might well require long baseline experiments:

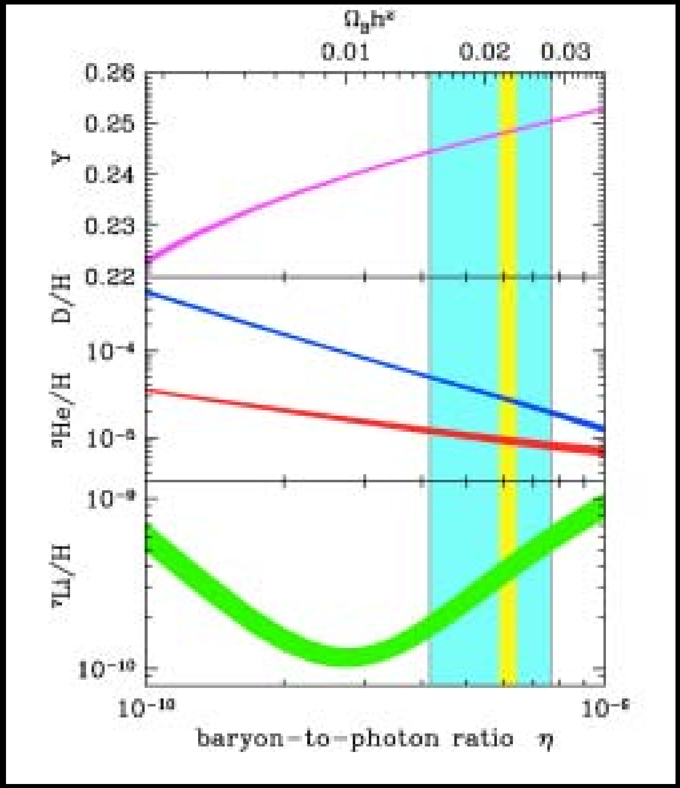
K2K, MINOS, CNGS …

Dark Matter

- A variety of astronomical observations tell us that most of the matter in the Universe is dark



Hubble Advanced Camera



Olive

Particle Dark Matter

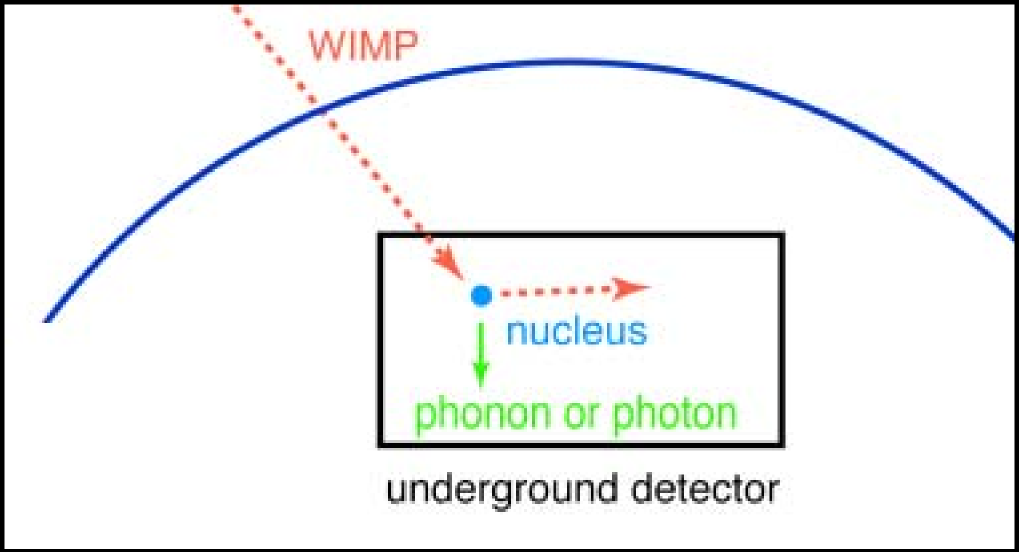
- WIMPs are likely candidates: stable, electrically neutral, weakly interacting, TeV-scale particles
- There are no such WIMPs in the Standard Model
- But most theories of electroweak unification have candidates
  - Lightest supersymmetric particle …
  - Lightest Kaluza-Klein particle ….

New TeV scale physics!

Particle Dark Matter

- We'd like to detect WIMPs in the lab
  - To show they're in the halo …
- And to produce them at an accelerator
  - To measure their properties …

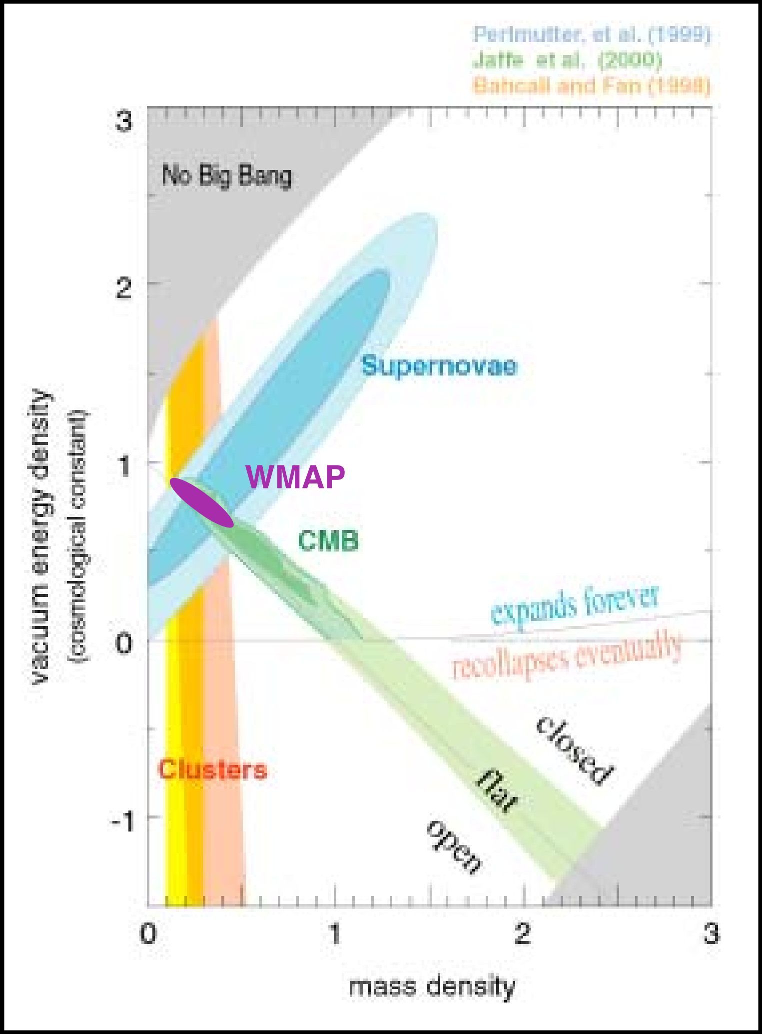
A linear collider is perfect for the task



Accelerating Universe

- Recent observations suggest expansion of the Universe is accelerating
- What can cause this?
  - Something that has *negative* pressure (!)

Dark Energy



Vacuum Energy

- Dark energy is the energy of the vacuum

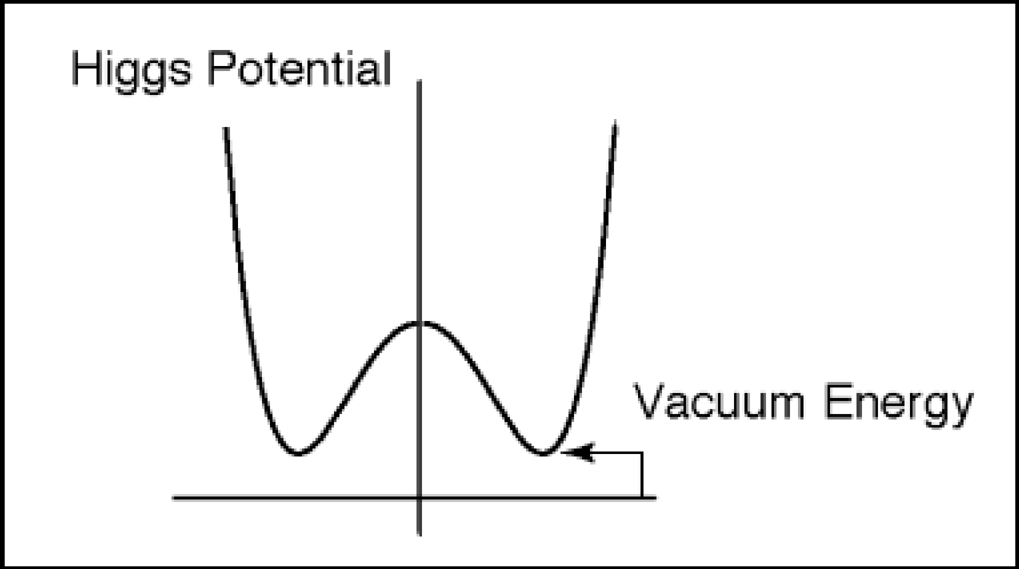
$$< T_{\mu\nu} > \propto \eta_{\mu\nu}$$

- It gives rise to negative pressure …

$$\eta_{\mu\nu} = \begin{pmatrix} 1 & & & \\ & -1 & & \\ & & -1 & \\ & & & -1 \end{pmatrix} \propto \begin{pmatrix} \rho & & & \\ & p & & \\ & & p & \\ & & & p \end{pmatrix}$$

Vacuum Energy

- The vacuum energy can come from a scalar field



- If the field is dynamical, the vacuum energy is called *quintessence*

Trouble!

- The dark energy is renormalized in quantum field theory. One calculates

$$\rho \sim {M_{Pl}}^4$$

instead of the observed value,

$$\rho \sim ((\mathrm{TeV})^2/M_{Pl})^4$$

- It's off by a factor of 10^{120} …

The worst prediction in physics!

Mystery of the Vacuum

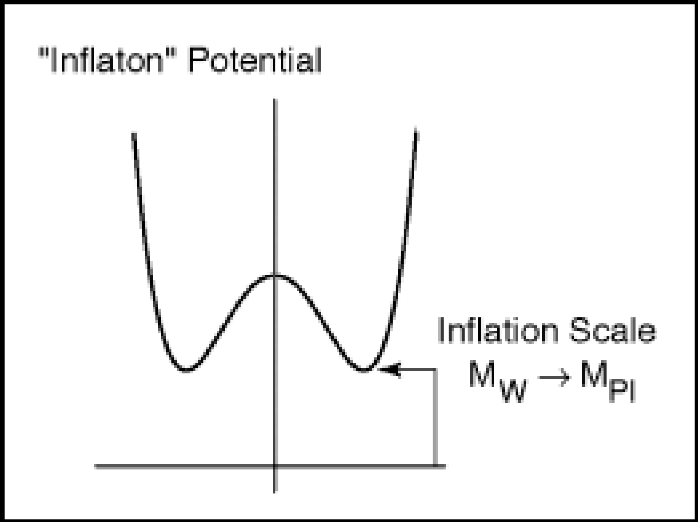
- The dark energy receives contributions from
  - Higgs field
  - QCD condensate
  - Everything else …
- The contributions all cancel. Almost.
  - Why? We need better measurements – and better ideas!

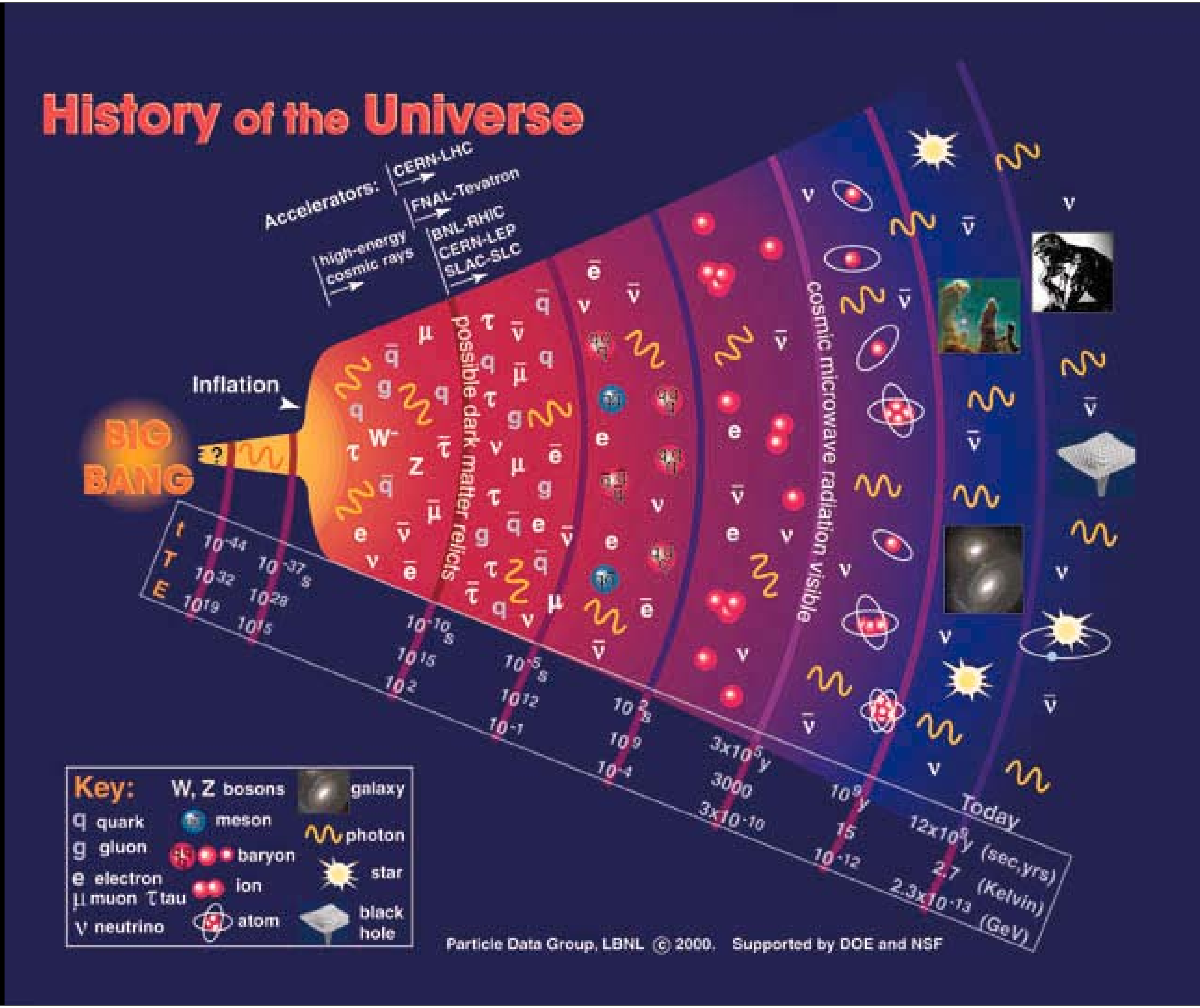
The problem lies at the heart of particle physics …

A Hint: Inflation

- The WMAP results are consistent with a period of exponential growth in the early Universe
- We believe the exponential growth is powered by vacuum energy. We have to take it seriously

There is no inflaton in the Standard Model …




History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relics
cosmic microwave radiation visible
t T E
10-44 10-37s 10-10s 10-5s 102s 3x105y 109y 12x109y (sec,yrs)
1032 1028 1015 1012 109 3000 15 2.7 (Kelvin)
1019 1015 102 10-1 10-4 3x10-10 10-12 2.3x10-13 (GeV)
Today
Key:
q quark
g gluon
e electron
μ muon τ tau
ν neutrino
W, Z bosons
meson
baryon
ion
atom
galaxy
photon
star
black hole
Particle Data Group, LBNL © 2000. Supported by DOE and NSF

TeV Scale

- Cosmology and particle physics both point to new physics at the TeV scale
  - Electroweak unification
  - Neutrino masses
  - CP violation
  - Dark matter
  - Dark energy
  - Inflation …

Exploring this physics will be the work of the 21st century

Conclusion

- Particle physics is entering an exciting new era
- The TeV scale will be a rich source of new physics
- Astrophysics and cosmology – and theory – provide clues, but we will need accelerators – the LHC and linear collider – to sort it all out
- And reveal the physics that is yet to come …


NOT YET THOUGHT OF
NOT YET THOUGHT OF
NOT YET THOUGHT OF
bosonic TC
composite Higgs
TC-TC
hypercolor
supercolor
techni-GIM
extended TC
pseudo NGB
effective SUSY
SUSY
NMSSM
MSSM + νR
ununified SM
axigluon
sterile ν
6th gen
5th gen
4th gen
lepto quark
heavy Majorana ν
vector-like family
fractionally charged
milli-charged
mono-pole
S,T,U
X Y
shadow matter
mirror symmetry
triplet Higgs
doubly charged Higgs
Type I
Type II
general 2HDSM
spontaneous CP
superweak
milli-weak
weinberg's 3HD
Majoron
axion
familon
NGB
saxion
axino
worm-hole
Extra dim
quintessence
k-essence
composite W,Z
contact int
string
hetero-tic
matrix M
IIB
N=2
N=4
N=8
Murayama